Extra- and Intracochlear Electrocochleography in Cochlear Implant Recipients

Dalbert, Adrian ; Pfiffner, Flurin ; Röösli, Christof ; Thoele, Konrad ; Sim, Jae Hoon ; Gerig, Rahel ; Huber, Alexander M

DOI: https://doi.org/10.1159/000438742

Original Paper

Audiology & Neurotology

Audiol Neurotol 2015;20:339–348
DOI: 10.1159/000438742

Received: May 6, 2015
Accepted after revision: July 15, 2015
Published online: September 5, 2015

Extra- and Intracochlear Electrocochleography in Cochlear Implant Recipients

Adrian Dalbert Flurin Pfiffner Christof Röösli Konrad Thoele Jae Hoon Sim
Rahel Gerig Alexander M. Huber

Department of Otorhinolaryngology, Head and Neck Surgery, University Hospital Zurich, University of Zurich, Zurich, Switzerland

Key Words
Electrocochleography · Intracochlear electrocochleography · Cochlear implantation · Hearing preservation

Abstract
Objective: To monitor cochlear function by extra- and intracochlear electrocochleography (ECoG) during and after cochlear implantation and thereby to enhance the understanding of changes in cochlear function following cochlear implantation surgery. ***Methods:*** ECoG responses to acoustic stimuli of 250, 500 and 1,000 Hz were recorded in 9 cochlear implant recipients with presurgical residual hearing. During surgery extracochlear ECoG recordings were performed before and after insertion of the cochlear implant electrode array. After insertion of the electrode array, intracochlear ECoG recordings were conducted using intracochlear electrode contacts as recording electrodes. Intracochlear ECoG recordings were performed up to 6 months after implantation. ECoG findings were correlated with findings from audiometric tests. ***Results:*** Extra- and intracochlear ECoG responses could be recorded in all subjects. Extracochlear ECoG recordings during surgery showed moderate changes. Loss or reduction of the ECoG signal at all three frequencies did not occur during cochlear implantation. During the first week following surgery, conductive hearing loss, due to middle ear effusion, led to a decrease in intracochlear ECoG signal amplitudes. This was not attributable to changes of cochlear function. All persistent reductions in ECoG response magnitude after normalization of the tympanogram occurred during the first week following implantation. Thresholds of ECoG signals were at or below hearing thresholds in all cases. ***Conclusion:*** Gross intracochlear trauma during surgery appears to be rare. In the early postoperative phase the ability to assess cochlear status by ECoG recordings was limited due to the regular occurrence of middle ear effusion. Still, intracochlear ECoG along with tympanogram recordings suggests that any changes of low-frequency cochlear function occur mainly during the first week after cochlear implantation. ECoG seems to be a promising tool to objectively assess changes in cochlear function in cochlear implant recipients and may allow further insight into the mechanisms underlying the loss of residual hearing.

Introduction

As cochlear implant performance has improved, patients with residual hearing have become candidates for this intervention. With this widening of indication, preservation of residual acoustic hearing has gained clinical importance. Hearing preservation is attempted for all co-

1420–3030/15/0205–0339$39.50/0

E-Mail karger@karger.com
www.karger.com/aud

Adrian Dalbert, MD
Department of Otorhinolaryngology, Head and Neck Surgery
University Hospital Zurich, Frauenklinikstrasse 24
CH–8091 Zurich (Switzerland)
E-Mail adrian.dalbert@usz.ch

chlear implant recipients with residual hearing nowadays [Carlson et al., 2011]. However, complete or partial loss of residual hearing still occurs in the majority of cochlear implant recipients [Anagiotos et al., 2015; Balkany et al., 2006]. The underlying mechanisms behind this hearing loss are controversial. An objective measurement to monitor intra- and postoperative changes in cochlear function could prove useful to enhance the understanding of mechanisms leading to such threshold shifts.

Electrocochleography (ECoG) is a method to objectively assess cochlear function. For clinical purposes, it has mainly been used in the diagnostic evaluation of Ménière's disease [Gibson et al., 1977]. Different potentials combine to produce the ECoG signal. The cochlear microphonic (CM) is produced by hair cells. The auditory nerve neurophonic (ANN) and the compound action potential represent neural responses. The summating potential is most likely a signal consisting of hair cell as well as neural components [Forgues et al., 2014; Sellick et al., 2003; van Emst et al., 1995]. The portion of the ECoG signal which occurs after the compound action potential and lasts for the duration of the acoustic stimulus is called the ongoing ECoG response. Recent studies defined the amplitude of the ongoing ECoG response as the sum of the response amplitude at the stimulation frequency (i.e. fundamental frequency or first harmonic) and the frequency of the second harmonic [Calloway et al., 2014; Fitzpatrick et al., 2014; Formeister et al., 2014; McClellan et al., 2014]. By this definition, the CM and the ANN contribute to the ongoing ECoG response. Summation or averaging of two ECoG responses with alternating starting phases is sometimes used to separate CM from ANN. However, it was recently demonstrated that this cannot be done at low frequency and high intensities [Forgues et al., 2014].

Objective assessment of cochlear trauma during cochlear implantation has been attempted by ECoG recorded from extracochlear sites [Calloway et al., 2014; Dalbert et al., 2015; Mandala et al., 2012; Radeloff et al., 2012]. Radeloff et al. evaluated the detection threshold of CM during cochlear implantation. They found changes in only 2 out of 4 patients with deep electrode array insertions despite complete hearing loss in all 4 patients 1 week after surgery. Mandala et al. found a correlation between a reduction in compound action potential amplitude during insertion of the electrode array and hearing preservation rates 4 weeks after surgery. In our own series [Dalbert et al., 2015], we evaluated the reduction of the ongoing ECoG response at suprathreshold intensities during cochlear implantation. These recordings indicated that gross intracochlear trauma only occurred in 1 out of 18 subjects.

To our knowledge, two reports discussing intracochlear ECoG recordings in humans have been published [Calloway et al., 2014; Campbell et al., 2014]. Calloway et al. correlated round window ECoG recordings with recordings made from a few millimeters inside the basal turn. Additionally, in 8 subjects a temporary lateral cochlear wall electrode was inserted for some distance into the scala tympani for intracochlear ECoG recordings. They found larger responses for intracochlear recording sites in the majority of subjects. On average signal amplitude increased with increasing electrode insertion depth. Campbell et al. used the cochlear implant itself as recording electrode. ECoG recordings in 5 subjects with some residual hearing after cochlear implantation proved the feasibility of intracochlear ECoG recordings through the cochlear implant.

The combination of extracochlear ECoG recordings during surgery and intracochlear ECoG recordings afterwards could allow a monitoring of cochlear function during and after cochlear implantation. The aim of this study was to evaluate such an approach and thereby to enhance the understanding of changes in cochlear function following cochlear implantation.

Materials and Methods

All subjects were adult candidates for cochlear implantation with a HiFocus™ Mid-Scala electrode array (Advanced Bionics, Stäfa, Switzerland) and provided written informed consent prior to their surgery. The study protocol was approved by the Ethical Committee of Zurich (KEK-ZH No. 2013-0317) and was written in concordance with the Helsinki Declaration.

Array Description

The HiFocus Mid-Scala electrode is a precurved array designed to achieve a position in the middle of the scala tympani. The diameter is 0.5 mm at the first contact (most apical) and 0.7 mm at the sixteenth (most basal). The electrode array is 18.5 mm long. It is designed for conventional cochlear implantation and cochlear implantation with intended preservation of residual hearing.

Audiometric Assessment

Pure-tone audiograms were conducted in accordance with ISO 8253-1. Presurgical pure-tone audiograms were performed within 6 weeks prior to surgery. Postsurgical pure-tone audiograms were performed 4 weeks after surgery and after each ECoG recording session. Tympanometry was conducted after each postoperative pure-tone audiogram. Air conduction thresholds were evaluated. Maximum audiometer output was 100 dB HL at 250 Hz and 120 dB HL at 500 and 1,000 Hz. If a response was considered as vibrotactile, or questionably vibrotactile, it was considered as no response. If at a certain frequency no response was present at the maximum output of the audiometer, the maximum output +5 dB was used [Balkany et al., 2006; Kiefer et al., 2004]. The average of hearing thresh-

olds at 250, 500 and 1,000 Hz was calculated to represent the remaining low-frequency hearing. Differences in hearing threshold were calculated from the mean low-frequency hearing. Three hearing preservation categories were defined by the change in mean low-frequency hearing [Balkany et al., 2006]: (1) complete hearing preservation (mean low-frequency hearing loss of ≤10 dB), (2) partial hearing preservation (mean low-frequency hearing loss of >10 dB but some remaining low-frequency hearing), and (3) no hearing preservation (complete loss of residual hearing). The differences in mean low-frequency hearing and the hearing preservation category were assessed in the last postoperative pure-tone audiogram. Hearing change in the contralateral ear was assessed to control for natural progression of hearing loss unrelated to cochlear implantation.

Surgery

Following a retroauricular incision, an anterior mastoidectomy and a posterior tympanotomy were performed in the usual fashion. After complete visualization of the round window, the recording electrode (Neurosign, Magstim Co., Whitland, UK) used for extracochlear ECoG recordings was placed on the promontory and remained in an unchanged position for the rest of the surgery (i.e. before and after electrode array insertion). Fixation of the recording electrode was achieved in the mastoidectomy cavity by bone wax. If the impedance of the recording electrode exceeded 10 kΩ, a resorbable gelatin sponge (Spongostan, Ethicon Inc., Sommerville, Mass., USA) was placed around the recording electrode. After completion of these steps, preinsertional extracochlear ECoG recordings were conducted. Afterwards the HiFocus Mid-Scala electrode array was slowly inserted through a round window approach and the insertion site sealed with periosteum. Extracochlear ECoG recordings were then repeated. Afterwards the recording electrode was removed and the incision closed in layers. During closure of the incision, intraoperative ECoG recordings were conducted from the intracochlear site using the HiFocus Mid-Scala electrode array as recording electrode.

ECoG Recordings

For extracochlear ECoG recordings, the Navigator Pro stimulation/recording device from Biologic Systems (Mundelein, Ill., USA) and the AEP software, version 7.0.0 (Mundelein), were used for acoustic stimulation and recordings. As recording electrodes, needle electrodes (Neurosign, Magstim Co.) were placed on the promontory ('positive') as described above, in the contralateral preauricular region ('negative') and on the forehead ('ground'). Acoustic stimuli were delivered by sterilized foam insert earphones (Biologic Systems). Responses to 400 tone bursts with alternating starting phases at 250, 500 and 1,000 Hz were recorded. Rise/fall times were 2 cycles and were shaped by a Blackman window. The plateau phase was 4 cycles at 250 Hz, 10 cycles at 500 Hz and 20 cycles at 1,000 Hz. Sound pressure for extracochlear ECoG recordings was 80 dB HL at 250 Hz, 85 dB HL at 500 Hz and 90 dB HL at 1,000 Hz. The recording window was 32 ms, starting 4 ms before stimulus presentation. The sampling rate was 8,000 Hz for the 250- and 500-Hz stimuli and 16,000 Hz for the 1,000-Hz stimuli. The recording amplifier's high pass filter was set at 10 Hz and the low pass filter at 5,000 Hz. For artifact rejection, a 47.5-μV threshold was selected.

For intracochlear ECoG recordings through the HiRes90K™ cochlear implant system (Advanced Bionics), the Bionic Ear Data Collection System (BEDCS; Advanced Bionics), version 1.18, was used. The BEDCS software was connected to the cochlear implant through the Clarion Programming Interface (Advanced Bionics) and the Platinum Series Speech Processor (Advanced Bionics). The BEDCS was configured for the cochlear implant system in recording mode with a gain of 1,000 Hz and a recording duration of 50 ms. The sampling rate was 9,000 Hz. The low pass filter was set at 5,000 Hz. If not otherwise declared, the most apical contact of the HiFocus Mid-Scala electrode array was used as recording electrode. In a subgroup of 6 subjects, ECoG recordings from different contacts along the electrode array were conducted. In such recordings a value of 0.5 μV, below the noise floor, was assigned for contacts with no measurable ECoG response. The ring electrode was used as reference electrode in all cases.

For acoustic stimulation in intracochlear ECoG recordings, the BEDCS software controlled the Clarion Programming Interface, providing a trigger input to the Navigator Pro device, thus allowing synchronous acoustic stimulation. Acoustic stimuli were delivered by foam insert earphones (Biologic Systems). Responses to 90–270 tone bursts with alternating starting phases at 250, 500 and 1,000 Hz were recorded. Rise/fall times were 2 cycles and were shaped by a Blackman window. Plateau phases were 5 cycles at 250 Hz, 14 cycles at 500 Hz and 32 cycles at 1,000 Hz. The stimulus rate was 10 Hz, with the maximum sound pressure 80 dB HL at 250 Hz, 85 dB HL at 500 Hz and 90 dB HL at 1,000 Hz. In postoperative recording sessions after 4 or more weeks, level series with 5- to 10-dB steps were taken until threshold. In recording sessions during surgery, after 1 day and after 1 week, threshold determination was not pursued and recordings were conducted at the maximum sound pressure level.

Postoperative intracochlear ECoG recordings were conducted only during regular follow-up visits. The study protocol did not allow additional visits for research purposes only. Recordings with disconnected loud speakers to control for electrical artifacts were conducted after each extra- and intracochlear ECoG recording session at maximum sound pressure. Sound pressure in the ear canal was monitored by a probe microphone (ER-7C, Etymotic Inc., Elk Grove Village, Ill., USA) placed near the tympanic membrane during all intraoperative recordings.

Data Analysis

AEP to ASCII software from Biologic Systems was used to export data from the AEP software. MATLAB (MathWorks Inc., Natick, Mass., USA) as well as GraphPad Prism V5.04 (GraphPad Software Inc., San Diego, Calif., USA) were used for further postprocessing.

The ECoG responses from rarefaction and condensation phases were stored separately. A difference curve was obtained by subtracting the average of the condensation from the average of the rarefaction phase and an alternating curve was obtained from the sum of both averages. A fast Fourier transform (FFT) was used to obtain the spectrum of each response. The response amplitude was measured at the frequency of the stimulus signal and at its first harmonic. The sum of both amplitudes was defined as the amplitude of the ongoing ECoG response at the frequency of the acoustic stimulus.

Based on the total response as defined by Fitzpatrick et al. [Calloway et al., 2014; Fitzpatrick et al., 2014; Formeister et al., 2015; McClellan et al., 2014], the sum of the magnitudes of valid ECoG responses at maximum sound pressure level for 250, 500 and 1,000 Hz was taken as a measure of the cochlear function at low frequencies. The sum is termed as the low-frequency ECoG response in the remainder of this article.

The noise floor was determined differently for extra- and intracochlear ECoG recordings. In extracochlear ECoG recordings, a re-

Table 1. Subject demographics and audiometric findings

Subject	Age, years	Side	Mean low-frequency hearing before surgery, dB HL	Change in mean low-frequency hearing, dB	Hearing preservation category	Change in mean low-frequency hearing on the contralateral side, dB
1	35	L	53.3	15	partial	3.3
2	70	R	93.3	–6.6	complete	–5
3	43	L	61.7	18.3	partial	no residual hearing
4	64	R	111.7	–5	complete	–5
5	36	R	66.7	6.6	complete	–1.7
6	21	L	90	6.7	complete	3.3
7	58	R	73.3	38.4	partial	–5
8	57	R	81.7	25	partial	3.3
9	52	L	103.3	15	no hearing preservation	no residual hearing

Change = Difference in mean low-frequency hearing between the preoperative and the last postoperative pure-tone audiogram.

sponse was considered valid if the amplitude exceeded the calculated noise floor + 3 standard deviations. The means of the noise floor and its standard deviations were calculated from all bins within 150–200 Hz and 300–350 Hz for 250 Hz, within 400–450 Hz and 550–600 Hz for 500 Hz, and within 900–950 Hz and 1,050–1,100 Hz for 1,000 Hz.

For intracochlear ECoG recordings, the noise floor was determined at the beginning of each recording session from the average of 270 recordings without acoustic input. Individual traces from each recording step were stored. The bootstrap method [Efron and Tibshirani, 1993] was utilized to construct the 99% confidence interval for each ECoG frequency component. For each bootstrap iteration, individual traces were drawn from the full set and recombined into a bootstrapped average trace. An FFT analysis was performed on the trace and stored. The resampling operation was repeated 1,000 times. The confidence interval for each FFT bin was computed by determining the observed 99% percentile value of the bootstrapped FFT outputs for each frequency bin. The presence of an ECoG component was judged as significant only if the frequency of the component related to the stimulus frequency and the amplitude of the component exceeded the confidence interval.

Results

Nine subjects were included. Subject 4 agreed to intraoperative recordings but declined further ECoG recordings during follow-up visits due to additional expenditure of time. In all subjects except subject 4, the etiology of hearing loss was unknown. Subject 4 had otosclerosis. All subjects had a history of hearing loss of more than 10 years. Subject demographics and audiometric findings are summarized in table 1.

Mean low-frequency hearing loss was 15.6 dB (range from –6.6 to 38.4 dB) 4 weeks after surgery. Pure-tone audiograms after 12 or more weeks showed no further decline in low-frequency hearing. On the contrary, subjects 2, 3, 5 and 6 showed a slight improvement in low-frequency hearing thresholds. The mean difference in low-frequency hearing thresholds between 4 and 12 or more weeks was –5.3 dB (range from –8.3 to 0 dB).

If residual hearing was present on the contralateral side, the mean loss in low-frequency hearing was 1.8 dB (range from –5 to 3.3 dB). Subjects 3 and 9 had no residual hearing on the contralateral side.

There were 4 subjects with complete hearing preservation, and 4 had hearing partially preserved. Only subject 9 showed a complete loss of residual hearing.

Tympanograms revealed middle ear effusion in all subjects, both 1 day and 1 week after surgery. Clinical inspection showed a hematotympanon in all cases. Tympanograms and otoscopic findings were normal in all subjects 4 or more weeks after surgery.

Extracochlear ECoG Recordings

Extracochlear ECoG recordings were obtained in all subjects. No valid responses were detectable at 500 and 1,000 Hz in subject 8 and at 1,000 Hz in subjects 2 and 6. Before insertion of the electrode array, the mean ECoG response amplitude relative to 0.1 μV was 21.5 dB at 250 Hz, 17.3 dB at 500 Hz and 15.5 dB at 1,000 Hz. Mean changes in ECoG response amplitude were 2.6 dB at 250 Hz (range from –2.4 to 7.4 dB), 2.6 dB at 500 Hz (range from –4.9 to 8.4 dB) and 3 dB at 1,000 Hz (from –0.7 to 8.6 dB). The mean change in low-frequency ECoG response was 1.8 dB with a range from –2 to 5.1 dB. Figure 1 shows an example for pre- and postinsertional ECoG signals at 250, 500 and 1,000 Hz recorded from the extracochlear site.

Intracochlear ECoG Recordings at Suprathreshold Intensities

Intracochlear ECoG recordings during surgery showed a valid ECoG signal in at least one frequency for all subjects. Subjects 1 and 8 showed no valid responses at 500 and 1,000 Hz, and subjects 2, 4, 6 and 9 showed no response at 1,000 Hz. Intraoperative recordings showed mean ECoG response amplitudes, relative to 0.1 μV, of 42.6 dB at 250 Hz, 37.4 dB at 500 Hz and 20.7 dB at 1,000 Hz. Figure 2 shows a typical intracochlear ECoG response (fig. 2a, b) and compares a signal recorded through the cochlear implant with a signal recorded from the extracochlear site (fig. 2c).

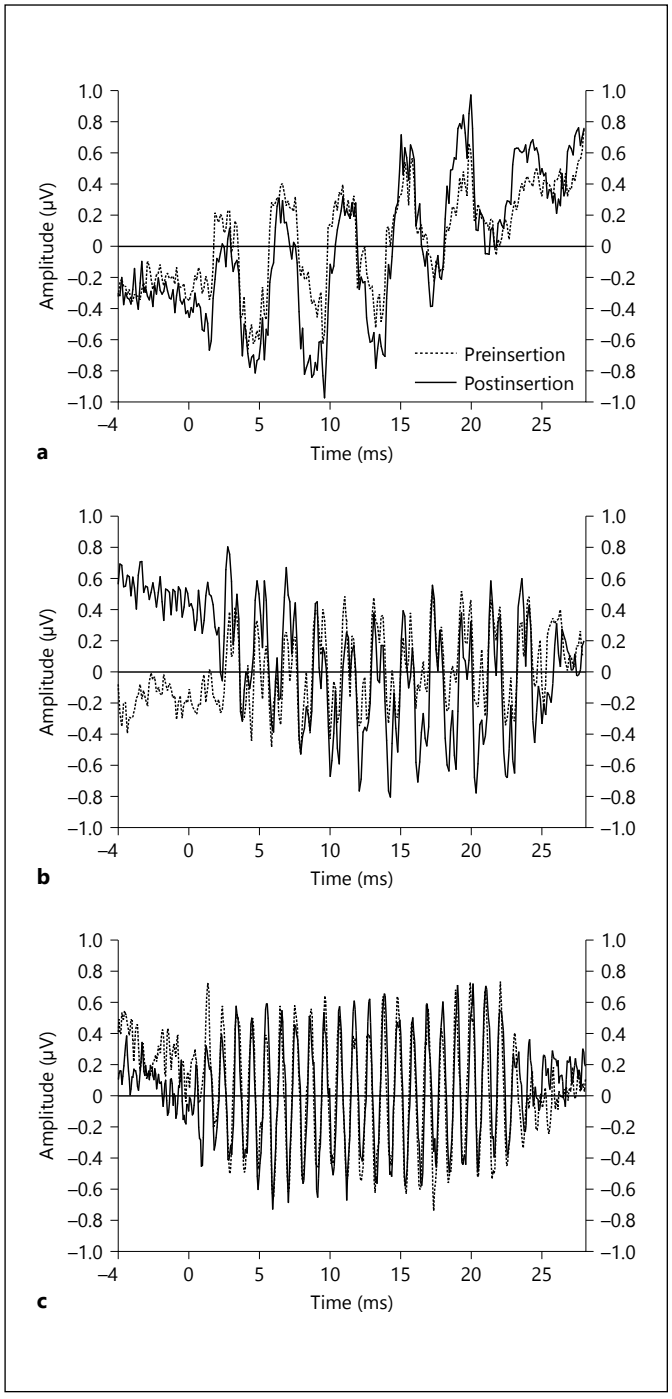

Fig. 1. Examples of ECoG signals recorded from the extracochlear site during cochlear implantation at 250 (**a**), 500 (**b**) and 1,000 Hz (**c**). The difference of both ECoG responses with alternating starting phases before (dotted line) and after (solid line) insertion of the cochlear implant electrode array is shown.

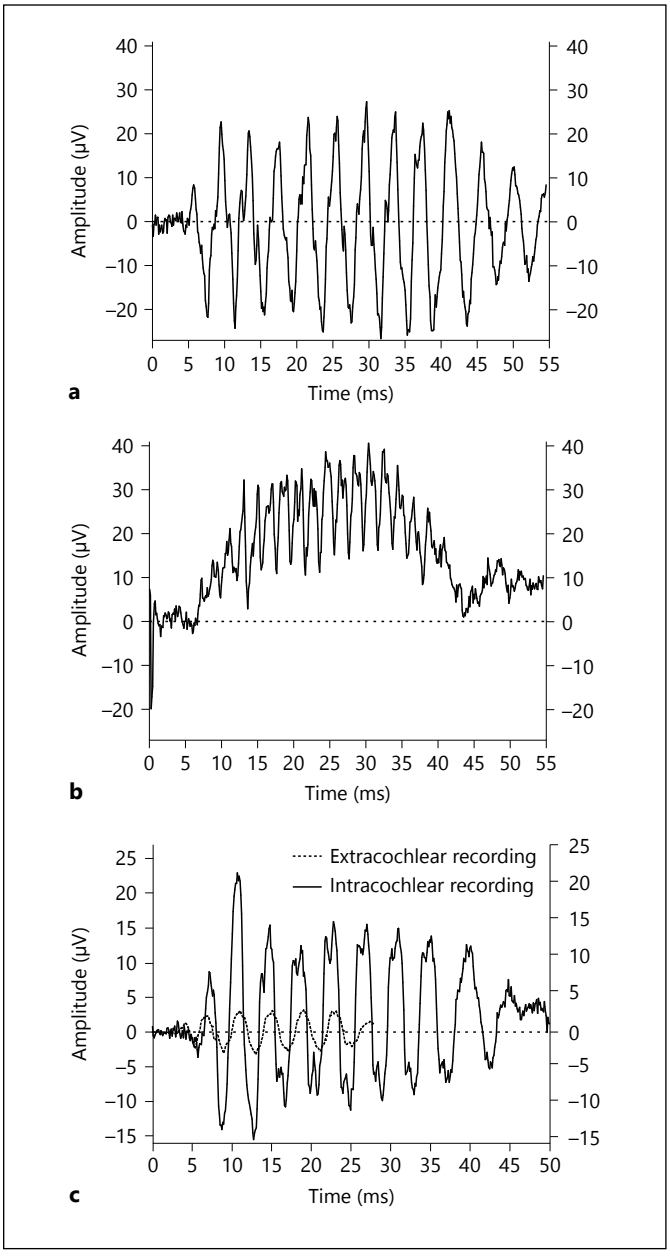

Fig. 2. ECoG signals recorded through the cochlear implant at 250 Hz and 80 dB HL in subject 3 (**a**, **b**) and subject 5 (**c**). **a** The difference of both ECoG responses with alternating starting phases. **b** The sum of both ECoG responses with alternating starting phases. **c** Comparison of the ECoG signal recorded after insertion of the electrode array from the extracochlear site and the ECoG signal recorded through the cochlear implant during surgery. The intracochlear recording shows a larger ECoG response. This can be explained by the closer location of the electrodes to the generators of the ECoG signal in intracochlear recordings compared to extracochlear recordings.

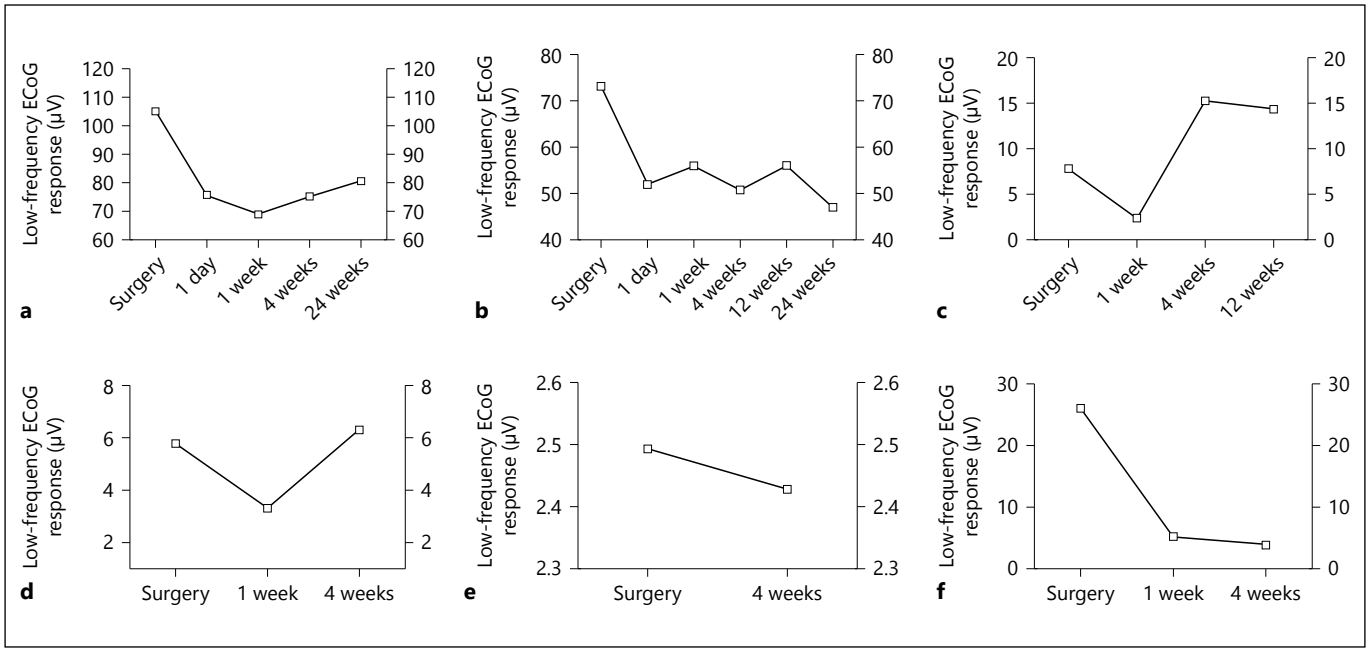

Fig. 3. Change over time in the low-frequency ECoG response recorded from the intracochlear site in subjects 3, 5, 6, 7, 8 and 9 (**a–f**). The x-axis represents the timeline, the y-axis the amplitude of the low-frequency ECoG response. Note the different scales of the y-axis in each plot.

Postoperative intracochlear ECoG recordings were conducted for 8 subjects. However, a comparison between intra- and postoperative ECoG recordings at suprathreshold intensities was not possible in subjects 1 and 2 since the stimulation level used during intraoperative ECoG recordings was not tolerated postoperatively.

Figure 3 shows the change in low-frequency ECoG response at suprathreshold intensities over time for subjects 3, 5, 6, 7, 8 and 9. Subjects 3 and 5 showed a similar pattern. Following a reduction of the response after 24 h, signals remained relatively stable until 24 weeks after surgery. For subject 6, the response was smaller after 1 week compared to intraoperative findings, but surpassed the magnitude of intraoperative recordings after 4 weeks. Then after 4 weeks the response remained stable. For subjects 7 and 9, a reduction of the response magnitude was detectable after 1 week. This reduction was reversible in subject 7 but remained stable in subject 9. Subject 8 had only 1 postoperative recording session after 4 weeks, showing an almost unchanged response.

Intracochlear ECoG recordings using different contacts of the cochlear implant's electrode array were conducted in subjects 1, 2, 3, 5 and 6 in 1 postoperative recording session after 12 or more weeks. Findings for different frequencies – normalized to the ECoG response magnitude at the most apical contact – are summarized in figure 4.

Comparison of Hearing Threshold and ECoG Signal

Thresholds of the ongoing ECoG signal were determined in postoperative recordings for 8 subjects. Comparison between hearing threshold and threshold of the ongoing ECoG signal revealed a threshold of the ongoing ECoG signal at or below the hearing threshold in all cases (fig. 5). Figure 6 shows examples of level series at all 3 frequencies.

Additionally, the change in the low-frequency ECoG response over time and the hearing preservation categories were compared in subjects 3, 5, 6, 7, 8 and 9. In subjects 3 and 5 with a reduction of the ECoG response after 24 h and afterwards stable conditions, partial (subject 3) and complete (subject 5) hearing preservation could be achieved. In subject 6 with complete hearing preservation, the low-frequency ECoG response showed a larger magnitude after 4 weeks when compared to intraoperative recordings. Partial hearing preservation in subjects 7 and 8 was associated with almost unchanged responses after 4 weeks. Subject 9 with a complete hearing loss showed a markedly reduced low-frequency ECoG re-

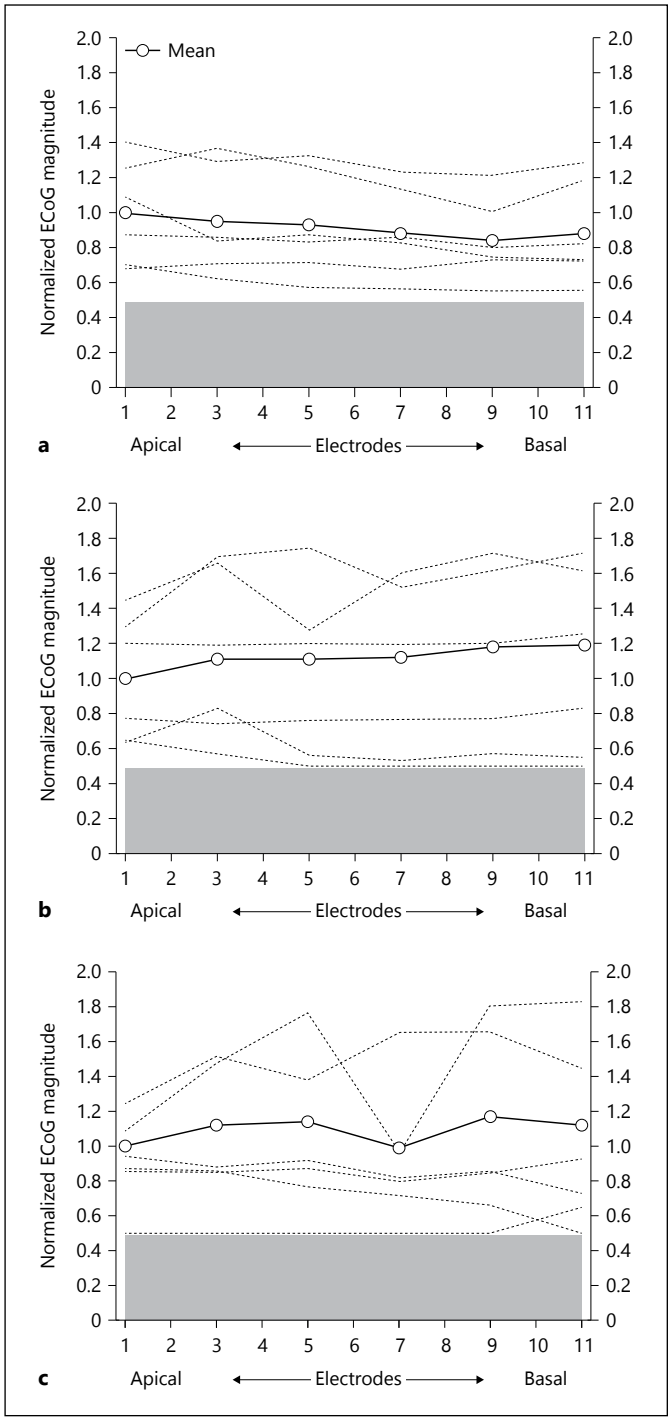

Fig. 4. ECoG response amplitudes measured from different contacts of the cochlear implant electrode array at 250 (**a**), 500 (**b**) and 1,000 Hz (**c**). Thin lines represent the individual ECoG signal amplitudes along the electrode array relative to the magnitude of the mean ECoG response in all subjects at a certain frequency. The amplitude of the mean ECoG response is presented relative to the amplitude recorded at the most apical electrode contact. The shaded part represents the part below the noise floor in ECoG recordings through the cochlear implant.

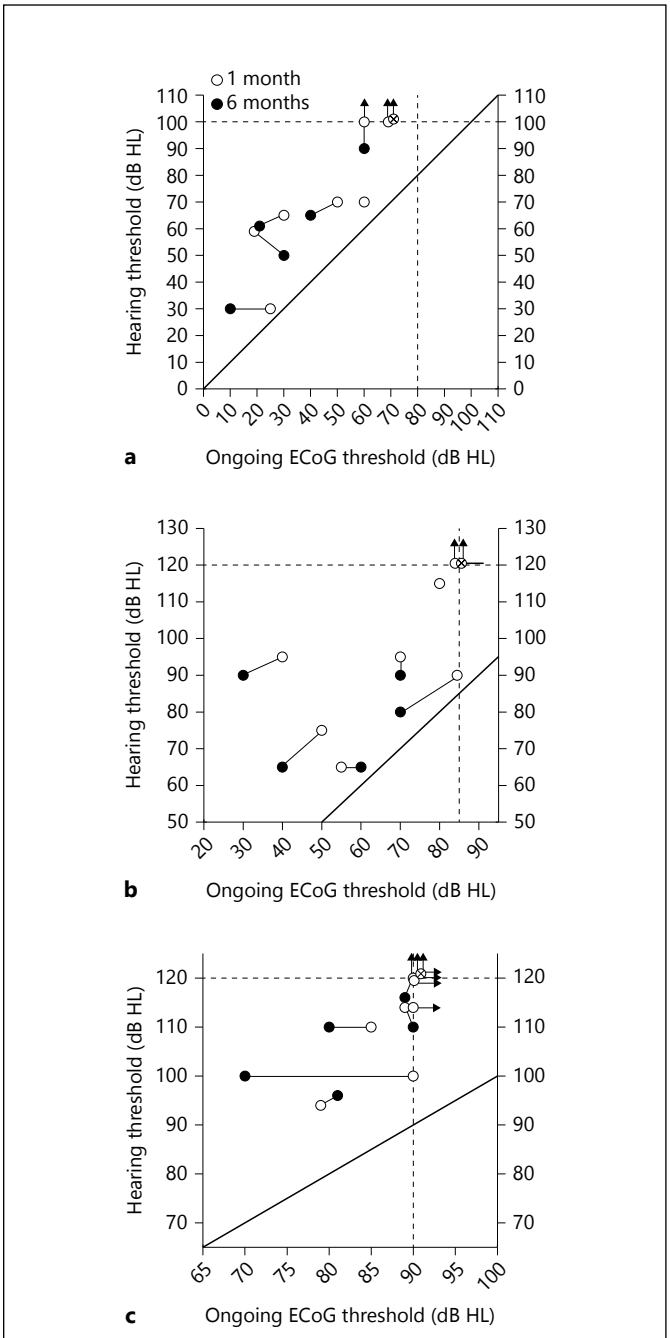

Fig. 5. Pure-tone audiogram thresholds compared to thresholds of the ongoing ECoG response at 250 (**a**), 500 (**b**) and 1,000 Hz (**c**). The x-axis represents the threshold of the ongoing ECoG response, the y-axis the hearing threshold. The maximum sound pressure in ECoG recordings and the maximum audiometer output are shown by the dashed lines. Arrows mark data points with no response at the maximum intensity in the ECoG recording, in the pure-tone audiogram or in both tests. Recordings in the same subject after 1 and 6 months are connected by lines. Circles with crosses represent the data points of subject 9 with complete loss of residual hearing.

Audiol Neurotol 2015;20:339–348
DOI: 10.1159/000438742

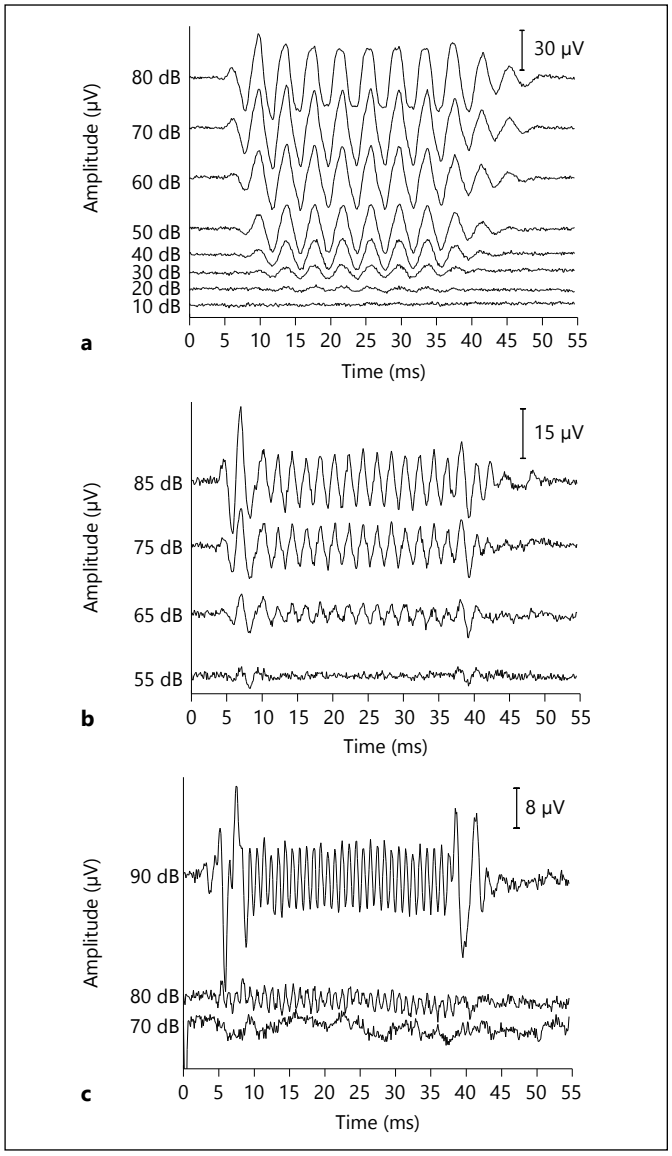

Fig. 6. Examples of level series recorded through the cochlear implant at 250 (**a**), 500 (**b**) and 1,000 Hz (**c**). The difference of both ECoG responses with alternating starting phases is shown down to threshold.

sponse after 1 week. This reduction persisted until 4 weeks after surgery and was associated with a complete loss of the ECoG signals at 500 and 1,000 Hz.

Discussion

This study assessed a combination of extra- and intracochlear ECoG recordings in cochlear implant recipients. Such recordings could allow a recurrent objective assessment of cochlear status during and after cochlear implantation and thereby could enhance the understanding of mechanisms responsible for the loss of residual hearing.

Extracochlear ECoG recordings were performed to assess the cochlear trauma during insertion of the electrode array. We monitored the ongoing ECoG signal at suprathreshold intensities as a decrease in this signal has been the most sensitive marker for cochlear trauma in animal studies [Adunka et al., 2010; Ahmad et al., 2012; Campbell et al., 2010; Choudhury et al., 2011, 2014; DeMason et al., 2012]. Gross intracochlear trauma (e.g. rupture of the basilar membrane) should cause an immediate reduction or loss of the ECoG signal [Adunka et al., 2010; Ahmad et al., 2012; Campbell et al., 2010; Choudhury et al., 2011, 2014; DeMason et al., 2012]. In our series, the largest decrease in the ECoG signal was 4.9 dB at 500 Hz. This was not associated with a decrease at 250 or 1,000 Hz. No subject showed a loss of ECoG response, or a decrease in ECoG signal, at all three frequencies. Therefore, according to extracochlear ECoG recordings before and after insertion of the cochlear implant electrode array, no gross cochlear trauma occurred during surgery.

The ability to assess changes of cochlear function by intracochlear ECoG was limited during the first week due to the regular presence of a hematotympanon. As the associated conductive hearing loss led to a decrease in the sound pressure reaching the inner ear, a decrease in the ECoG signal resulted which is most likely not attributable to changes in cochlear function. It was not possible to distinguish between changes of the ECoG signal caused by middle ear effusion and those caused by intracochlear processes. However, in cases where the reduction of the ECoG response was not reversible after normalization of the tympanogram, it is plausible to assume that changes represent, at least partly, a deterioration of cochlear function. Therefore, our results suggest that changes in cochlear function mainly occur during the first week after cochlear implantation. Findings in subjects 3 and 5 suggest that while no change in extracochlear recordings occurred during surgery, loss of cochlear function took place during the first 24 h after surgery. This finding fits well with the hypothesis that early inflammatory responses play a prominent role in the loss of residual hearing [Kel et al., 2013].

Subject 6 showed an increase in the low-frequency ECoG response after 4 weeks compared to intraoperative recordings. As intraoperative ECoG recordings through the cochlear implant were conducted during closure of

the incision, a rapid progression of middle ear effusion could be an explanation for this.

ECoG signal magnitudes after 4 or more weeks remained relatively stable in all subjects. In concordance, pure-tone audiograms showed stable thresholds without progressive loss of residual hearing. In the literature, such a progressive loss of residual hearing over a long time period is reported to occur in about 20% of cochlear implant recipients [Gstoettner et al., 2006].

With the technique presented here a quantitative comparison between intra- and extracochlear ECoG recordings is not feasible because of the use of two different recording systems having different signal-to-noise ratios. By design, the cochlear implant amplifier has a higher noise floor than regular amplifiers such as the Biologic Navigator Pro used in this study for extracochlear ECoG recordings. This means ECoG signals had to be larger, or more averages had to be accumulated, in intracochlear ECoG recordings to have comparable signal-to-noise ratios between both systems. However, the fact that the mean ECoG response amplitude relative to 0.1 μV was 18.1 dB in extracochlear recordings and 33.5 dB in recordings through the cochlear implant supports the assumption that ECoG recordings from an intracochlear site usually produce larger signals. This finding is in concordance with results published by Calloway et al. [2014] and can most likely be explained with a closer location to the generators of the ECoG signal in intracochlear recording.

In concordance with previous studies, intracochlear recordings from different intracochlear sites showed findings varying based on stimulus frequency. Calloway et al. [2014] found a clear trend toward larger signals at 500 Hz with increasing insertion depth of the temporary lateral wall electrode. However, when recording from different intracochlear sites using different contacts of the electrode array, Campbell et al. [2015] could not detect such a clear trend for 1,000 Hz but showed similar results for 500 Hz. Compared to signal amplitudes from the middle of the electrode array, basal contacts detected an increase in CM in 1 out of 3 subjects and of ANN in 2 out of 3 subjects. As the distinction between CM and ANN is not possible at low frequencies [Forgues et al., 2014], we only assessed the magnitude of the ongoing ECoG signal. However, in 4 recordings at 500 Hz and at 1,000 Hz, we could also detect larger responses of the ongoing ECoG signal in recordings from more basal contacts. On average, the expected trend of larger amplitudes for more apical contacts was present at 250 Hz. This was not the case at 500 and 1,000 Hz. A larger neural contribution due to proximity to the auditory nerve, or as outlined by Campbell et al. [2014] the extent and nature of the foreign body reaction to the electrode array, could play a role.

In concordance with previous reports [Campbell et al., 2014; Choudhury et al., 2012], comparison between intracochlear recordings and behavioral hearing thresholds revealed ECoG signal thresholds at or below behavioral hearing thresholds in all cases. As suggested by Choudhury et al. [2012], this is probably caused by the CM which as a hair cell response does not directly translate into hearing. Accordingly, postoperative changes of the low-frequency ECoG response over time did not directly reflect changes of the hearing threshold. However, in subject 9, where there was a complete loss of residual hearing, postoperative ECoG recordings showed a large decrease in the low-frequency ECoG response and a complete loss of ECoG responses at 500 and 1,000 Hz, indicating a marked loss of cochlear function.

Conclusion

Findings suggest that gross cochlear trauma during surgery is rare and that changes in cochlear function for low-frequency regions mainly occur during the early postoperative phase. With the technique we present, the regular presence of middle ear effusion in the first days following surgery limits the ability to assess the extent of deterioration in cochlear function in the early postoperative phase. Overall, ECoG recordings from extra- as well as intracochlear sites along with tympanogram findings are able to provide additional information on changes in cochlear status for cochlear implant recipients and seem to hold great potential to enhance our understanding of the mechanisms leading to loss of residual hearing in cochlear implant recipients.

Acknowledgments

We would like to thank Kanthaiah Koka, Leo Litvak and Patrick Boyle from Advanced Bionics for their technical contribution and great support throughout this project.

Disclosure Statement

This study was partially funded by Advanced Bionics, Stäfa, Switzerland.

References

Adunka OF, Mlot S, Suberman TA, Campbell AP, Surowitz J, Buchman CA, Fitzpatrick DC: Intracochlear recordings of electrophysiological parameters indicating cochlear damage. Otol Neurotol 2010;31:1233–1241.

Ahmad FI, Choudhury B, De Mason CE, Adunka OF, Finley CC, Fitzpatrick DC: Detection of intracochlear damage during cochlear implant electrode insertion using extracochlear measurements in the gerbil. Laryngoscope 2012;122:636–644.

Anagiotos A, Hamdan N, Lang-Roth R, Gostian AO, Luers JC, Huttenbrink KB, Beutner D: Young age is a positive prognostic factor for residual hearing preservation in conventional cochlear implantation. Otol Neurotol 2015; 36:28–33.

Balkany TJ, Connell SS, Hodges AV, Payne SL, Telischi FF, Eshraghi AA, Angeli SI, Germani R, Messiah S, Arheart KL: Conservation of residual acoustic hearing after cochlear implantation. Otol Neurotol 2006;27:1083–1088.

Calloway NH, Fitzpatrick DC, Campbell AP, Iseli C, Pulver S, Buchman CA, Adunka OF: Intracochlear electrocochleography during cochlear implantation. Otol Neurotol 2014;35: 1451–1457.

Campbell AP, Suberman TA, Buchman CA, Fitzpatrick DC, Adunka OF: Correlation of early auditory potentials and intracochlear electrode insertion properties: an animal model featuring near real-time monitoring. Otol Neurotol 2010;31:1391–1398.

Campbell L, Kaicer A, Briggs R, O'Leary S: Cochlear response telemetry: intracochlear electrocochleography via cochlear implant neural response telemetry pilot study results. Otol Neurotol 2015;36:399–405.

Carlson ML, Driscoll CL, Gifford RH, Service GJ, Tombers NM, Hughes-Borst BJ, Neff BA, Beatty CW: Implications of minimizing trauma during conventional cochlear implantation. Otol Neurotol 2011;32:962–968.

Choudhury B, Adunka OF, Awan O, Pike JM, Buchman CA, Fitzpatrick DC: Electrophysiologic consequences of flexible electrode insertions in gerbils with noise-induced hearing loss. Otol Neurotol 2014;35:519–525.

Choudhury B, Adunka OF, Demason CE, Ahmad FI, Buchman CA, Fitzpatrick DC: Detection of intracochlear damage with cochlear implantation in a gerbil model of hearing loss. Otol Neurotol 2011;32:1370–1378.

Choudhury B, Fitzpatrick DC, Buchman CA, Wei BP, Dillon MT, He S, Adunka OF: Intraoperative round window recordings to acoustic stimuli from cochlear implant patients. Otol Neurotol 2012;33:1507–1515.

Dalbert A, Sim JH, Gerig R, Pfiffner F, Roosli C, Huber A: Correlation of electrophysiological properties and hearing preservation in cochlear implant patients. Otol Neurotol 2015; 36:1172–1180.

DeMason C, Choudhury B, Ahmad F, Fitzpatrick DC, Wang J, Buchman CA, Adunka OF: Electrophysiological properties of cochlear implantation in the gerbil using a flexible array. Ear Hear 2012;33:534–542.

Efron B, Tibshirani RJ: An Introduction to the Bootstrap. Boca Raton, Chapman & Hall/ CRC, 1993.

Fitzpatrick DC, Campbell AT, Choudhury B, Dillon MP, Forgues M, Buchman CA, Adunka OF: Round window electrocochleography just before cochlear implantation: relationship to word recognition outcomes in adults. Otol Neurotol 2014;35:64–71.

Forgues M, Koehn HA, Dunnon AK, Pulver SH, Buchman CA, Adunka OF, Fitzpatrick DC: Distinguishing hair cell from neural potentials recorded at the round window. J Neurophysiol 2014;111:580–593.

Formeister EJ, McClellan JH, Merwin WH 3rd, Iseli CE, Calloway NH, Teagle HF, Buchman CA, Adunka OF, Fitzpatrick DC: Intraoperative round window electrocochleography and speech perception outcomes in pediatric cochlear implant recipients. Ear Hear 2015;36: 249–260.

Gibson WP, Moffat DA, Ramsden RT: Clinical electrocochleography in the diagnosis and management of Ménière's disorder. Audiology 1977;16:389–401.

Gstoettner WK, Helbig S, Maier N, Kiefer J, Radeloff A, Adunka OF: Ipsilateral electric acoustic stimulation of the auditory system: results of long-term hearing preservation. Audiol Neurotol 2006;11(suppl 1):49–56.

Kel GE, Tan J, Eastwood HT, Wongprasartsuk S, O'Leary SJ: Early cochlear response and ICAM-1 expression to cochlear implantation. Otol Neurotol 2013;34:1595–1602.

Kiefer J, Gstoettner W, Baumgartner W, Pok SM, Tillein J, Ye Q, von Ilberg C: Conservation of low-frequency hearing in cochlear implantation. Acta Otolaryngol 2004;124:272–280.

Mandala M, Colletti L, Tonoli G, Colletti V: Electrocochleography during cochlear implantation for hearing preservation. Otolaryngol Head Neck Surg 2012;146:774–781.

McClellan JH, Formeister EJ, Merwin WH 3rd, Dillon MT, Calloway N, Iseli C, Buchman CA, Fitzpatrick DC, Adunka OF: Round window electrocochleography and speech perception outcomes in adult cochlear implant subjects: comparison with audiometric and biographical information. Otol Neurotol 2014;35:e245–e252.

Radeloff A, Shehata-Dieler W, Scherzed A, Rak K, Harnisch W, Hagen R, Mlynski R: Intraoperative monitoring using cochlear microphonics in cochlear implant patients with residual hearing. Otol Neurotol 2012;33:348–354.

Sellick P, Patuzzi R, Robertson D: Primary afferent and cochlear nucleus contributions to extracellular potentials during tone-bursts. Hear Res 2003;176:42–58.

Van Emst MG, Klis SF, Smoorenburg GF: Tetraethylammonium effects on cochlear potentials in the guinea pig. Hear Res 1995;88:27–35.